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Dynamic Characteristics of Joined Steel and Carbon Fiber-Reinforced Plastic Tubes: Experimental and Numerical Investigation

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ABSTRACT

The fundamental frequencies and mode shapes of steel and carbon fiber–reinforced plastic (CFRP) cylindrical shells with steel inserts were investigated using finite element analysis and modal testing. The free-free boundary condition was tested with modal testing using the roving hammer method and verified by finite element analysis using ABAQUS. The results show good agreement between the testing and finite element analysis in both natural frequencies and mode shapes. Then, the vibrational behavior of cylindrical shells with steel/CFRP lap joints for simply supported-free and clamped-free edge conditions was studied using the verified finite element modeling, and the effects of lengths and thicknesses of composite cylinders and steel inserts on the free vibration of joined steel/CFRP were investigated. The results show that the vibrational behavior of the CFRP shell and its dimensions has a major influence on natural frequencies and mode shapes of the joined shells.

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1. Introduction

Because of the higher dynamic performance (the higher specific stiffness and damping characteristics) of carbon fiber–reinforced plastic (CFRP) structures compared to steel ones, the use of CFRP is increasing in mechanical structures such as machine tool spindles and the power-transmission shafts of aircraft, ships and cars, robotic arms, etc. In most of these structures, one would join the composite sections with metallic structures, and, thus, the dynamic behavior of joined steel-composite structures is of main importance.

The joining of composite materials is of major interest to industry for structural integrity. Because adhesive bonding is a practical technique for composite materials, the behavior of adhesively bonded composite structures requires special attention. The effects of environmental phenomena, such as temperature, moisture, sea water, fire, and ultraviolet exposure [1-8], and the effects of mechanical characteristics, such as fatigue and fracture [9, 10], on steel/CFRP structures are widely studied. Yang and Du [11] assessed the fatigue life of joints of graphite-epoxy bonded to titanium under spectrum loading. The vibration of laminated plates with adhesive joints was studied by Yeh and You [12]. Ko et al. [13] used an iso-parametric adhesive interface element in the vibration analysis of adhesively bonded structures. Botelho [14] used modal experiments to evaluate the damping behavior of continuous fiber/metal composite materials. Yuceoglu and Ozerciyes [15] studied the free vibrations of bonded single lap joints in composite shell panels. The vibration of laminated shells has been reported by numerous researchers [16-20].

Agarwal et al. [21] performed an experimental study on the wet thermo-mechanical behavior of steel-CFRP joints. They also tested adhesives for steel-CFRP joints under sustained loading and temperature cycles [22]. Kouchakzadeh and Shakouri [23] used continuity conditions at the joining section of the cones to formulate and solve the problem of free vibration of joined cross-ply laminated conical shells. The general case of joined conical shells can be assumed to be similar to that of joined cylindrical shells. Colombi and Fava [24] studied the fatigue behavior of tensile steel/CFRP joints. Al-Mosawe et al. [25] investigated the strength of CFRP/steel double strap joints under impact loads using genetic programming. Although the problem of joined steel-CFRP systems has been studied in open literature, the vibration problems of steel/CFRP systems with adhesive joints has had few investigations and needs more attention.

In this study, the fundamental frequencies and mode shapes of CFRP cylindrical shells with steel inserts were investigated using finite element (FE) analysis and modal testing. The free-free boundary condition was tested through modal testing. The modal testing was performed through the roving hammer method, and the results were verified by FE analysis using the ABAQUS software. Then, the vibrational behavior of the cylindrical shells with steel/CFRP joints for simply supported-free and clamped-free edge conditions was studied using the verified FE modeling, and the effects of the cylindrical composite and steel shell lengths and thicknesses on the free vibration of steel-CFRP joints were investigated.

2. Test Sample

The test sample was a cylinder made of CFRP and a small steel cylinder that were inserted into a composite cylinder, as shown in Figure 1. The CFRP part was made of 16 asymmetric layers of carbon-epoxy with 55 and -55° angles. The cylindrical steel was T400 Series Stainless Steel that was attached to the end of the cylindrical CFRP shell using epoxy adhesive. Table 1 presents the geometrical dimensions of the test sample.

The mechanical properties of the sample are presented in Table 2 [26, 27].

3. Finite Element Analysis

The finite element (FE) analysis was conducted by the ABAQUS software with the four-node shell element S4R, which has six degrees of freedom at each node, three translational displacements in the nodal directions, and three rotational displacements about the nodal axes. S4R is a linear element formulation with reduced integration, and hourglass control. The structures of the cylinders are made of carbon/epoxy laminates, and laminar layup was used to model the composite shell. Using the Lanczos method, the eigenvalue problem was solved. Since the results of the FE analysis are affected by the number of elements involved, the convergence of the results versus the number of total elements was checked and is presented in Figure 2. Different boundary conditions, including free-free, simply supported-free, and clamped-free boundary conditions, were examined.

Table 1. Dimensions of cylindrical CFRP and steel shells

CFRP shell			Steel shell			
L_C	D_C	t_C	L_S	D_S	t_S	H
0.52 m	11.0 cm	4 mm	0.18 m	10.9 cm	2.5 mm	0.13 m

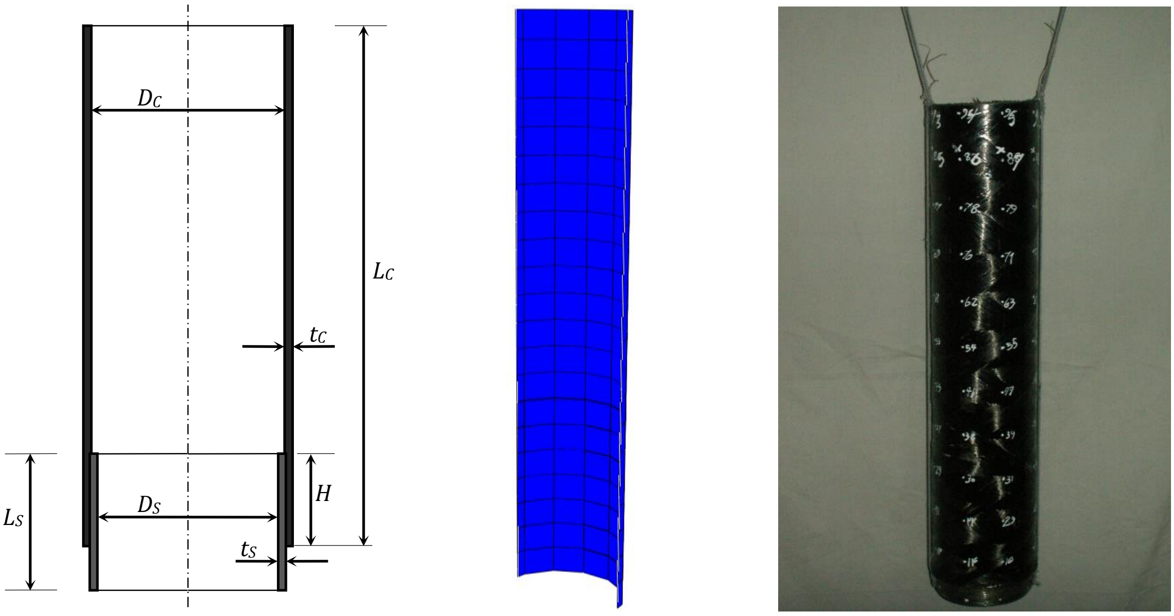

Figure 1. The test sample and cross-sectional view of the FE model

Table 2. Mechanical properties of CFRP lamina and steel sections [26, 27]

CFRP		T400 Series Stainless Steel	
Longitudinal modulus, E_1 (GPa)	132	Elastic modulus, E (GPa)	290
Transverse modulus, E_2 (GPa)	7.9	Poisson's ratio, ν	0.3
Shear modulus, G_{12} (GPa)	3.77	Density, ρ (kg/m^3)	6700
Poisson's ratio, ν_{12}	0.34		
Density, ρ (kg/m^3)	1600		

4. Modal Testing

In order to compare and verify the FE or analytical results, modal testing with an impact hammer was used to measure the structure's dynamic properties. A 16-input channel analyzer was used for data acquisition and frequency response function (FRF) extraction (see Figure 3).

4.1 Supports

In the modal test, the free-free boundary condition was selected and realized by hanging the test sample with elastic cables. The use of this system of damping is such that the natural frequencies of the suspension strings are far from frequency of the test sample. The suspension system frequencies must be smaller than 0.2 times the fundamental frequency [28].

4.2 Excitation and Accelerometers

A piezoelectric accelerometer was used for response measurement. Because the weight of the test sample was relatively low, the moving mass of the shaker may have imposed a considerable effect on the natural frequencies of the sample. Therefore, the roving hammer method was used for excitation of the sample at 96 points. The schematic diagram for the experimental modal test is shown in Figure 3.

4.3 Extraction of Modal Properties

Each FRF was evaluated after averaging three measurements in order to reduce noise. Then the polyMAX curve-fitting method [29] was used to identify frequencies, damping, and mode shapes.

5. Results and Discussion

5.1 Comparison of Experiment and FE Results

In order to check the accuracy of the present analysis, the natural frequencies obtained from FE analysis are compared in Table 3 with the experimental results with free-free boundary conditions. The results show agreement between the test and calculated results in the first three modes. Identifying the mode shape is of crucial importance in the case of shells. The high modal density makes it difficult to compare experimental and numerical models using natural frequencies only; therefore, the visualization of modes is mandatory.

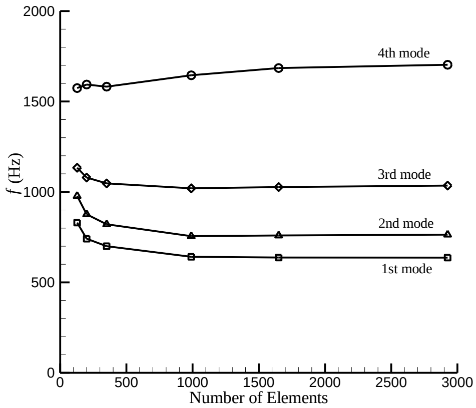

Figure 2. Mesh convergence study of FE analysis

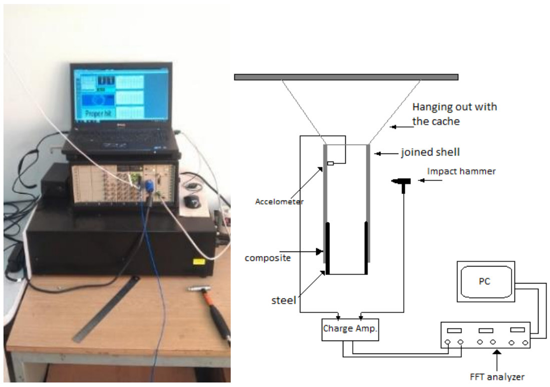

Figure 3. Apparatus and schematic diagram of modal testing

Figure 4 shows the mode shapes extracted from modal testing and FE analysis for the cylindrical steel-to-CFRP joined shells with free-free boundary conditions. Results show an acceptable accordance of the experimental and numerical modes, and it ensures that we can trust the numerical results instead of expensive experimental tests.

5.2 Parametric Study

5.2.1 Effect of Cylindrical CFRP Shell Length on the Natural Frequency

This section describes how the the effects of the CFRP shell length (normalized with the effects of the CFRP shell's cylindrical diameter [L_C/D_C]) on the natural frequencies of the joined shells were evaluated using the FE and test results. In this analysis, the ratio L_S/D_S remains constant and is set to its primary value of 1.65. The results are shown in Figure 5. In addition, the effects of changed boundary conditions are shown in Figures 6 and 7.

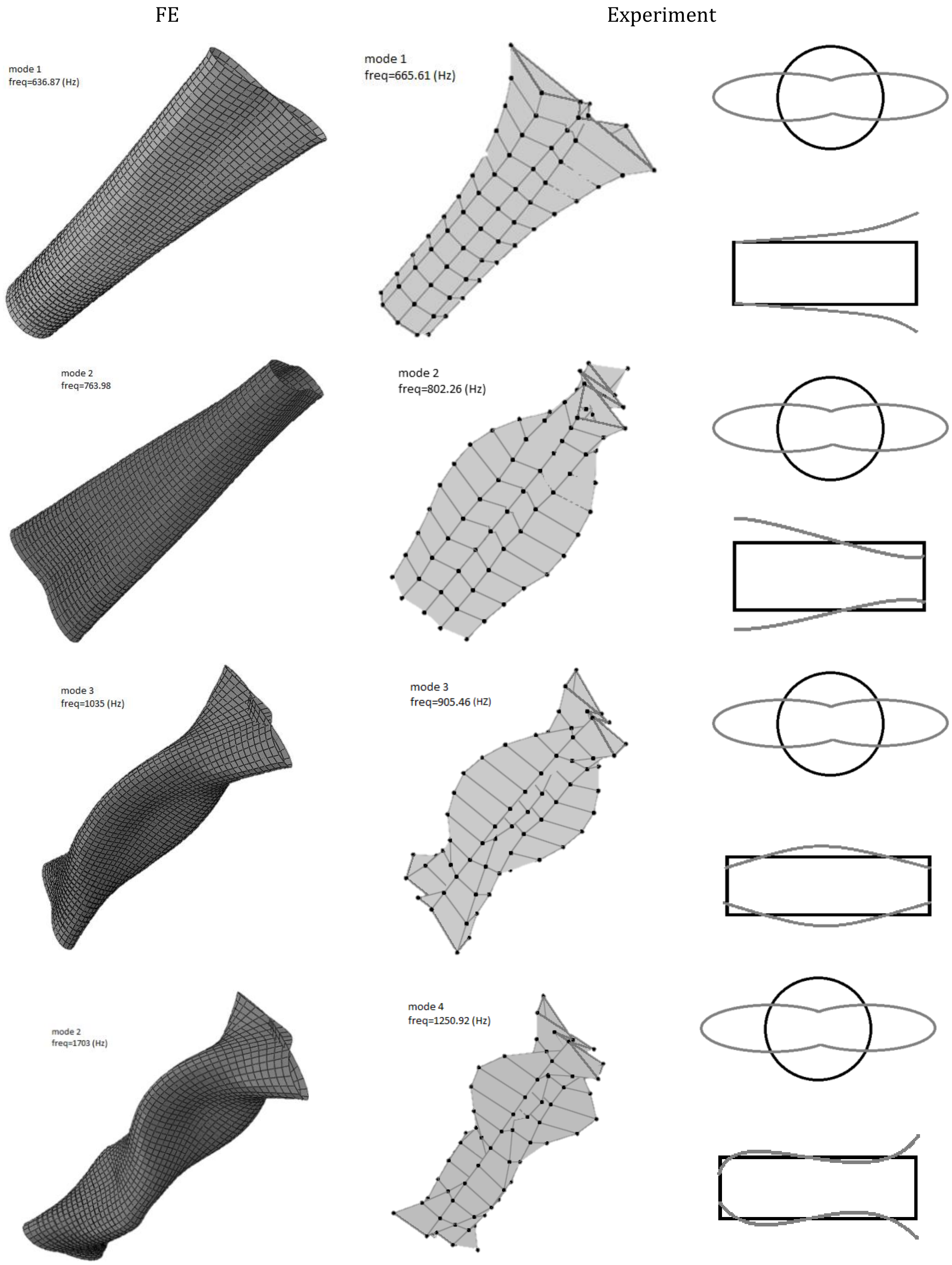

Figure 4. Comparison of modal testing and FE mode shapes with free-free boundary conditions

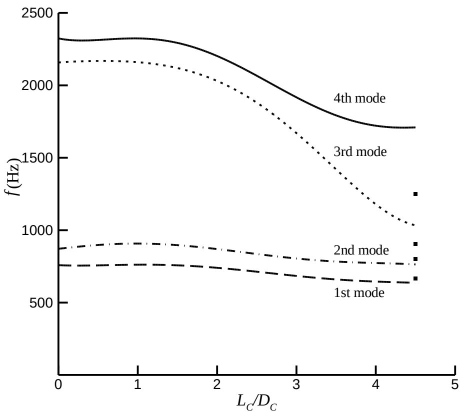

Figure 5. Effect of CFRP shell length on the natural frequencies (Hz) of cylindrical steel-to-CFRP joined shells with free-free boundary conditions (the solid squares represent the test results)

As can be seen, increasing the length of the CFRP section decreases the natural frequency. This is because of the decreased stiffness of the structure. However, at the lower modes, the CFRP length has less effect on the natural frequency in comparison with higher modes.

The change in the type of boundary conditions from free-free to simply supported-free and clamped-free caused an increase in natural frequencies. However, the overall behavior of the natural frequencies against CFRP length remains unchanged and the drop in curves are more considerable at higher modes. In addition, it can be noted that when the length of the CFRP shell is relatively short (i.e. L_C is less than L_S), the natural frequencies of joined shells do not change significantly in all three boundary conditions.

Table 3. Comparison of the natural frequencies of cylindrical CFRP-to-steel joined shells with free-free boundary conditions

	Experiment (Hz)	FE (Hz)	Error (%)
1st mode	666	637	4.35
2nd mode	802	764	4.74
3rd mode	905	1035	14.36
4th mode	1251	1703	36.13

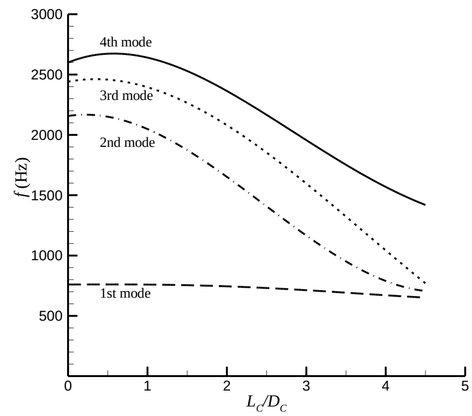

Figure 6. Effect of CFRP shell length on the natural frequencies (Hz) of cylindrical steel-to-CFRP joined shells with simply supported-free boundary conditions

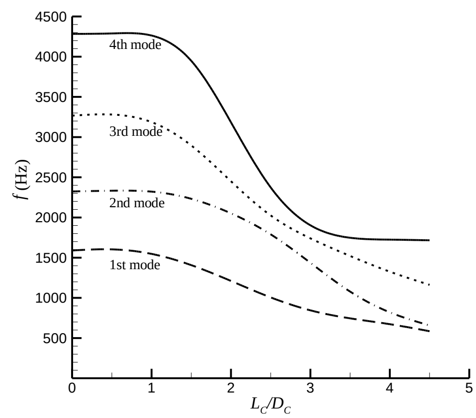

Figure 7. Effect of CFRP shell length on the natural frequencies (Hz) of cylindrical steel-to-CFRP joined shells with clamped-free boundary conditions

5.2.2 *The Effect of Steel Insert Length on the Natural Frequencies*

The effects of a dimensionless length of steel insert (L_S/D_S) on the natural frequencies of the joined shells were evaluated with the results from the FE and testing. In this analysis, the L_C/D_C ratio of the CFRP shell remained constant and its primary value was set to 4.72.

The effects of steel shell length (L_S/D_S) with free-free, simply supported-free, and clamped-free boundary conditions are shown in Figures 8–10. It can be seen from the above figures that the steel shell length at this region (L_S/D_S from 0 to 1.65) has a small effect on the natural frequencies.

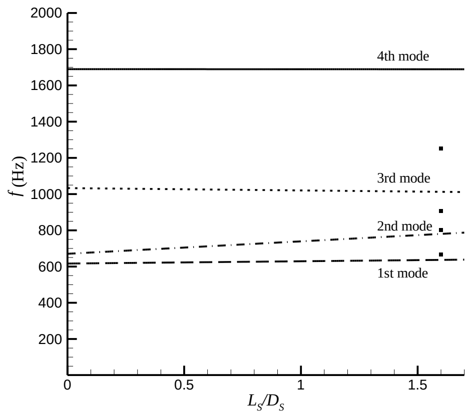

Figure 8. Effect of steel shell length on the natural frequency (Hz) of cylindrical steel-to-CFRP joined shells with free-free boundary conditions (the solid squares represent the test results)

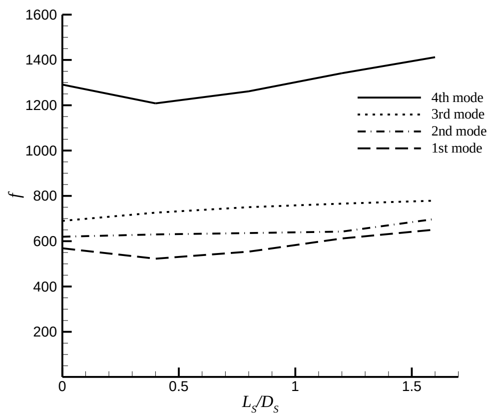

Figure 9. Effect of steel shell length on the natural frequency (Hz) of cylindrical steel-to-CFRP joined shells with simply supported-free boundary conditions

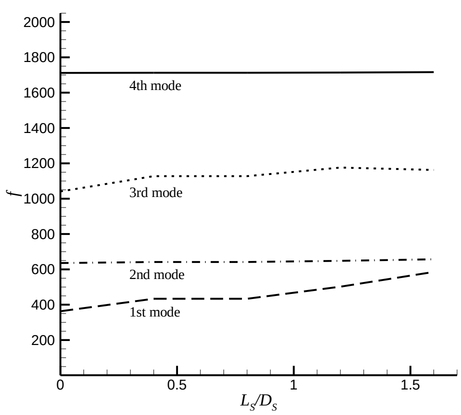

Figure 10. Effect of steel shell length on the natural frequency (Hz) of cylindrical steel-to-CFRP joined shells with clamped-free boundary conditions

This is because the dominant modes of joined shells are the mode shapes of the CFRP section in the region of study, and the length of the steel shell does not affect the mode shapes and frequencies.

5.2.3 Effect of Shell Thicknesses on Natural Frequency

Figure 11 shows the effects of the dimensionless thickness (t_C/D_C) of the CFRP shell on the first natural frequency of the joined shell structure with free-free boundary conditions. The first natural frequency of the joined shells increases as the dimensionless thickness increase for different lengths of the CFRP shell. However, as shown in Figure 12, the dimensionless thickness (t_S/D_S) of the steel shell has a limited effect on the first natural frequency under free-free boundary conditions. This is because the steel section is stiffer than the CFRP section and has less of an effect on natural frequencies and mode shapes (See Figure 4).

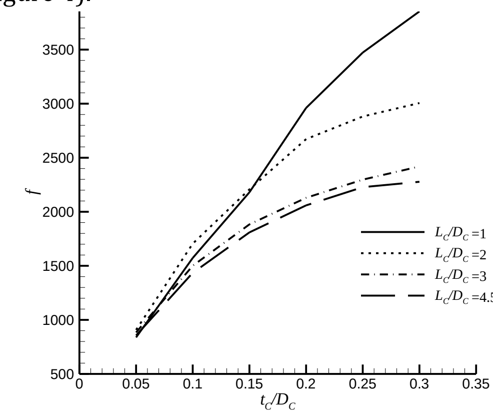

Figure 11. Effect of CFRP shell thickness on the first natural frequency (Hz) of joined shells with free-free boundary conditions

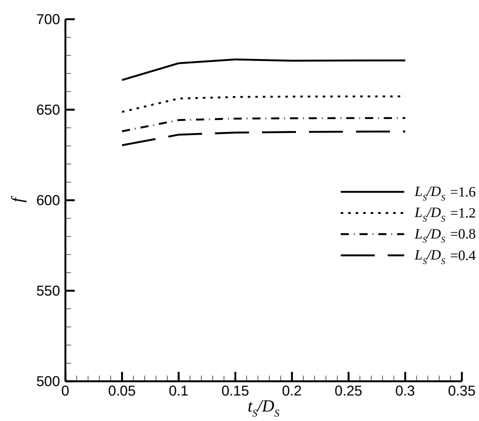

Figure 12. Effect of steel shell thickness on the first natural frequency (Hz) of joined shells with free-free boundary conditions

6. Conclusions

Because of its wide range of applications, the dynamic behavior of steel/CFRP with adhesive joints is an important problem in joined shells. In the present study, the natural frequencies and mode shapes of CFRP cylindrical shells with steel inserts were investigated using FE analysis and modal testing. The free-

free boundary condition was tested with modal testing and verified by FE analysis using ABAQUS. The results show agreement between test and FE analysis in both natural frequencies and mode shapes. Then, the simply supported-free and clamped-free edge conditions were studied using the verified FE modeling. The major conclusions from this study are as follows:

1. The vibrational behavior of the CFRP shell has a major influence on the natural frequencies and mode shapes of the joined shells. The length of the CFRP shell has a significant effect on the vibrational behavior of the joined shells, especially at the higher modes.
2. The thickness of the CFRP shell is very effective in the vibrational behavior of joined shells, and the fundamental frequency of the joined structure increases as the CFRP shell thickness increases.
3. The steel insert thickness has no considerable effect on the natural frequencies in the region this study was done, and changes in the length of the steel shell cause small changes in natural frequencies in both lower and higher modes.

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